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Stabilization of femtosecond optical parametric oscillators for infrared frequency comb generation

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Synchronously pumped optical parametric oscillator (SP-OPO) is one of the most common techniques to generate femtosecond frequency combs in the mid-infrared region. Stable long-term operation of an SP-OPO requires active locking of the OPO resonator round-trip time to the pump pulse interval. A simple modulation-free locking method based on stabilization of narrow-band frequency-doubled power of the SP-OPO output comb is demonstrated in this Letter. The method relies on the strong dependency of frequency-doubled power on spectral shape of the comb, leading to better stability of the comb envelope spectrum than the commonly used dither-and-lock method.

Mid-infrared (MIR, $\lambda > 2.5$ µm) optical frequency combs are needed in particular for molecular spectroscopy [1-4]. Because direct generation of MIR frequency combs by mode-locked lasers is beyond the state of the art, nonlinear optics is commonly used to convert near-infrared femtosecond frequency combs into the mid-infrared region [5]. One of the most popular methods for this is to use a synchronously pumped OPO, which can be either singly resonant [6] or doubly resonant [7]. A doubly resonant SP-OPO for frequency comb generation is usually operated at degeneracy, where the signal and idler combs resonating in the OPO cavity become indistinguishable and are automatically phase locked to the pump comb. This provides a combination of large instantaneous MIR bandwidth, low pump threshold, and ease of implementation [7]. In addition to spectroscopy, the degenerate SP-OPO has proven useful in other high-impact applications, such as combinatorial optimization by coherent optical processing [8, 9].

Figure 1 schematically shows the experimental setup of the degenerate SP-OPO used in this work. This setup, which is a typical example of an Er-laser-pumped femtosecond MIR comb generator, is described in detail in Ref. [10]. Oscillation of SP-OPO is possible only when the round-trip time of the OPO resonator is synchronized to the pump repetition rate f_r. Owing to the doubly resonant operation, as well as to intracavity group delay dispersion (GDD), the oscillation is typically attained for a few discrete lengths of the SP-OPO cavity, see Fig. 2 and Ref. [11]. Each oscillation peak shown in Fig. 2 corresponds to a different MIR output spectrum, depending on at which wavelengths the GDD maintains synchronism with the pump pulse train. Substantial variation of the shape of the MIR envelope spectrum is observed already when slightly changing the resonator length within an oscillation peak. This is illustrated in Fig. 3, which shows the MIR output spectrum of our degenerate SP-OPO when the OPO cavity length is locked to two different points within one of the oscillation peaks. Spectral variation as a function of cavity detuning is also observed with singly-resonant SP-OPOs [12]. Note that in the case of a degenerate doubly-resonant SP-OPO only the envelope spectrum of the MIR comb changes, not the comb line positions, which are tightly locked to the pump comb [10, 13].

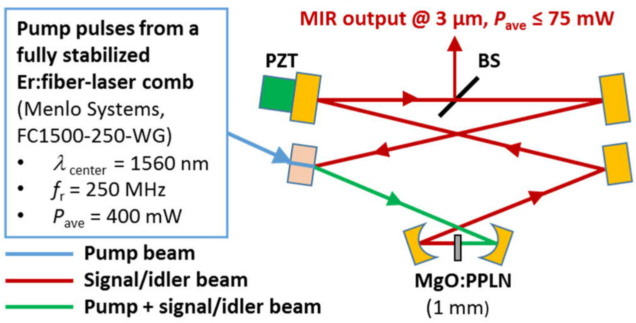

Fig. 1. Schematic of the degenerate SP-OPO [10]. About 35% of the resonating signal/idler power is coupled out with a pellicle beam splitter (BS). The nonlinear crystal is MgO-doped periodically poled lithium niobate (MgO:PPLN). Piezoelectric actuator (PZT) is used for fine adjustment of the cavity length.

Passive thermal locking can often maintain SP-OPO oscillation for several minutes or more [7, 14], albeit with poor stability of the output power and spectrum, unless a crystal of large thermal effect, such as GaAs, is used [15]. In practice, active locking of the resonator length is usually needed. In the following, we briefly discuss problems related to the known locking methods, especially regarding the instability of comb envelope spectrum. After that, we propose and demonstrate a new locking method, which results in high spectral stability while being simple to implement and use.

The most straightforward approach for active locking of an SP-OPO resonator length is side-of-fringe locking, which however does not give access to the maximum output power. A typical solution to lock on top of the oscillation peak is to use the “dither-and-lock” method [7]. In this method, either the pump repetition/offset frequency or the OPO cavity length is modulated with a sinusoidal signal, such that an asymmetric error signal (1f signal, Fig. 2) is obtained after phase-sensitive detection of the SP-OPO output power at the modulation frequency f. Modulation of the pump laser cannot be used if high stability of the comb teeth positions is required, for instance when the intended application is dual-comb spectroscopy [4]. Therefore, the modulation is typically done by dithering the OPO cavity length with a piezoelectric actuator (PZT). In either case, the modulation leads to an oscillation of the output spectrum, owing to sensitivity of the spectrum to cavity length detuning (Fig. 3) [12]. Another problem of this method is that the top of an oscillation peak can be irregular [11, 14] or flat, such as peak D in Fig. 2, prohibiting precise locking to the peak.

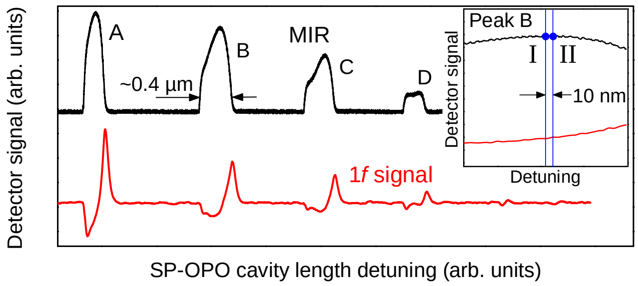

Fig. 2. In black: MIR output power of the degenerate SP-OPO as a function of cavity length detuning. The detuning between adjacent oscillation peaks is equal to the pump wavelength, 1560 nm [7, 13]. In red: 1f signal obtained after phase-sensitive detection of the MIR power. The inset shows a detail of the top of peak B, with vertical blue lines denoting the limits of cavity-length change with a modulation amplitude of 5 nm.

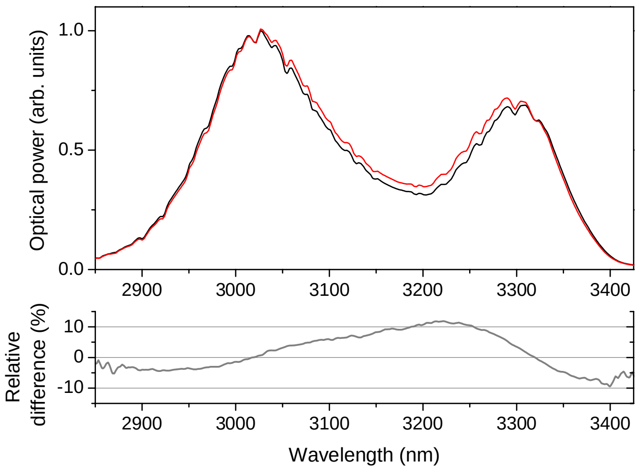

Fig. 3. Upper panel. The red and black traces show MIR comb envelope spectra measured with two different SP-OPO cavity lengths that are separated by only 10 nm. Lower panel: Relative difference of the two spectra of the upper panel.

The 1f signal of Fig. 2 was recorded using a cavity-length modulation amplitude of 15 nm, but even a smaller modulation can be sufficient for locking purposes. With the experimental setup used in this work, robust long-term locking by the dither-and-lock method typically requires a modulation amplitude of about 5 nm in cavity length when using a modulation frequency of 50 to 200 Hz. Similar modulation amplitudes have been used with other degnerate SP-OPOs, with both OPO and pump laser cavity length modulation [16, 17]. The extremes of ±5 nm cavity length modulation around the center of oscillation peak B are indicated by points I and II in the inset of Fig. 2. The respective end points of the resulting spectral fluctuation of the MIR output comb are shown by the red and black traces in Fig. 3. Despite the smallness of cavity length change, the spectral fluctuation is significant, up to more than 10% at some wavelengths. This spectral instability can cause severe limitations in, e.g., direct frequency comb spectroscopy.

Here, we propose and demonstrate a simple modulation-free locking method, which overcomes the problems associated with direct side-of-fringe locking and dither locking. In this method, a narrow portion of the MIR output spectrum is frequency doubled. As the frequency-doubled (second harmonic, SH) power strongly depends on the spectral shape of the MIR comb, the comb spectrum can be stabilized and synchronous pumping maintained by stabilizing the SH power. The principle of the locking scheme is shown in Fig. 4. The output voltage of the SH power detector (Thorlabs DET10N/M) is compared with a reference voltage to generate the error signal, which is used as an input for the locking electronics (integrating amplifier) in the usual manner. Depending on which part of the spectrum is frequency doubled, the maximum of the SH power is obtained at different cavity length detunings relative to the MIR power, i.e., relative to an SP-OPO oscillation peak. This is demonstrated in Fig. 5 for two different SH wavelengths. In both cases, frequency doubling was done using a 20-mm long Mg:PPLN crystal that provides a phase-matching bandwidth of approximately 5 nm, as measured as the full width at half maximum of the SH spectrum. This spectral bandwidth is only about 2 % of the total span of the comb, and hence sufficient to obtain a high spectral sensitivity of the SH signal for locking purposes without any additional spectral filtering.

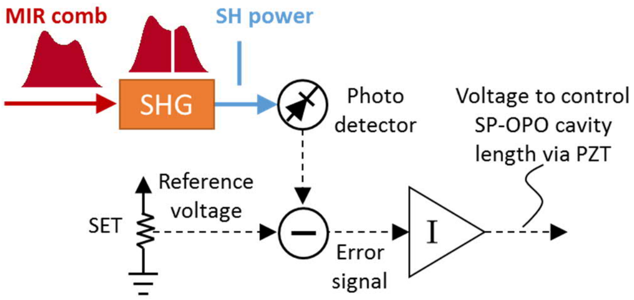

Fig. 4. Block diagram of the locking instrumentation. SHG is the nonlinear optical crystal for second harmonic generation. Electric signals are denoted by dashed lines. I = integrating amplifier.

In all measurements reported here, the entire power of the MIR comb – which is appr. 20 to 35 mW of average power after filtering out the pump beam with an uncoated Ge plate – was directed through the SHG crystal. After the crystal, the MIR and SH beams were separated with a dichroic mirror. The SH parameters and filtering were adjusted such that a few µW of SH power reached the detector. Owing to the narrow SHG bandwidth and small power level required by the SH power detector, the MIR comb spectrum is not substantially altered by the SHG process.

As illustrated in Fig. 5. for three different SP-OPO oscillation peaks, linear SH signal slopes can be obtained despite the irregularities of the MIR oscillation peaks. The shape of the stabilized output spectrum can be varied either by changing the reference voltage for locking, or by frequency doubling a different portion of the MIR spectrum – both of these adjustments vary the lock point relative to the OPO oscillation peak. Locking on top of the oscillation peak, or to any other point within the peak, can thus be realized without modulation.

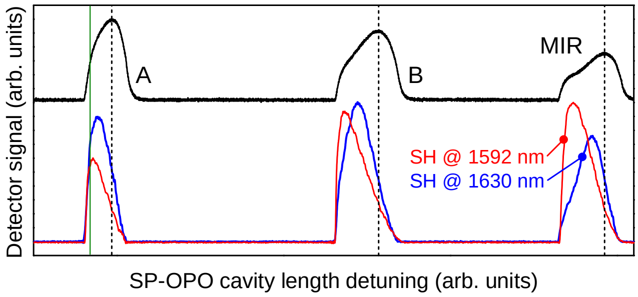

Fig. 5. In black: MIR output power of the degenerate SP-OPO as a function of cavity length detuning. In red and blue: Second harmonic (SH) power obtained by narrow-band frequency doubling of the MIR comb at two different wavelengths. The dashed vertical lines denote the oscillation peak centers. The green vertical line is another possible lock point, see text for details. In all measurements reported here, the SH signal at 1630 nm was used for locking.

The comb spectra reported here were measured with a Fourier Transform Infrared (FTIR, Bruker IFS 120 HR) spectrometer using a spectral resolution of 5 cm^{-1} and a measurement time of approximately 10 s. The FTIR measurement speed is far from sufficient to see the modulation arising from the cavity-length dither. Therefore, the measurements of Fig. 3 were carried out using the modulation-free SH locking method, and the effect of 5 nm modulation amplitude required for the dither-and-lock method was deduced from the measurements of two lock points that correspond to a 10 nm difference in the SP-OPO cavity length. These points, called point I and point II, are the same as those indicated in the inset of Fig. 2. While a peak-to-peak spectral power fluctuation of more than 10% is caused by the cavity length dithering, a remarkably high stability is obtained when using the new modulation-free SH locking method. This was confirmed by measuring the SH-locked spectrum consequently 10 times at each lock point, over a time span of 2.5 min. The recorded spectra are shown in Fig. 6. The standard deviation of power is less than 1.5% at all wavelengths, as illustrated in the lower panel of the figure. For comparison, the same measurement was carried out with the dither-and-lock method, using a modulation frequency and amplitude of 60 Hz and 5 nm, respectively. The resulting best case spectra are shown in Fig. 7. For this best case measurement the standard deviation of the spectra was 7%, but a maximum standard deviation of over 10% was more typical. These results imply that approximately a ten-fold improvement in spectral stability can be obtained by using the SH locking method instead of the dither-and-lock method. Stability of the total MIR average output power is good with both methods, the standard deviation of the total power being typically less than 1% in 1 h, see Fig. 8 and [10].

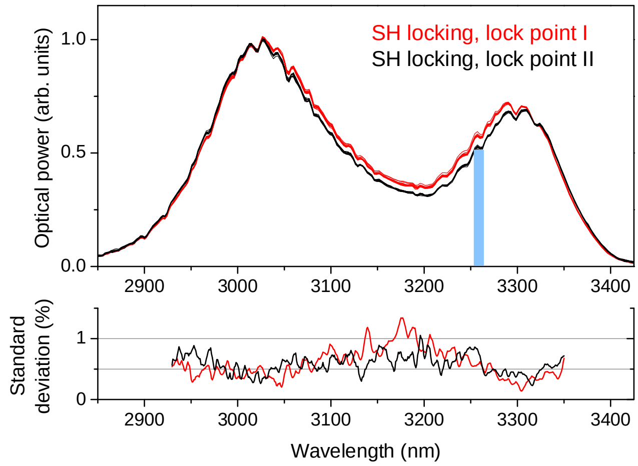

Fig. 6. Upper panel: Ten MIR comb envelope spectra recorded consequently at each lock point, point I and point II, using the modulation-free SH method. Fig. 3 shows the average spectra of these recordings. The blue bar indicates the SH phase-matching bandwidth used for locking. Lower panel: Standard deviations of the spectra.

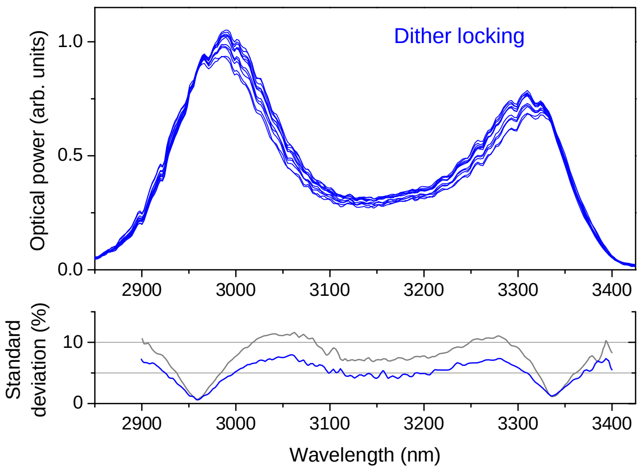

Fig. 7. Upper panel: Ten MIR comb envelope spectra recorded consequently using the dither-and-lock method. Lower panel, in blue: The standard deviation of the spectrum. The gray curve shows the standard deviation of another measurement set, which was done using a slightly different lock point.

Although the spectral stability of dither locking is ultimately limited by the modulation amplitude, part of the improvement provided by the SH method is due to the possibility of using more aggressive locking. For instance, in the SH-locked measurements reported here, a slew rate of 1.3 mm/s was used for the cavity-length feedback. This is 2 to 3 orders of magnitude faster than the feedback speed of a typical MIR dither-and-lock instrumentation, which is limited by the maximum speed of sinusoidal cavity length modulation, and in our case also by the electrical bandwidth of 120 Hz of the MIR detector (thermopile, Heimann Sensor GmbH). In order to reach a high spectral stability, the SH generation phase-matching wavelength was chosen to match with a wavelength of large sensitivity of the MIR spectrum to cavity length detuning, see the blue bar of Fig. 6. Furthermore, it is advantageous to choose an

SH wavelength that produces a clean and linear error signal slope around the desired lock point. To illustrate the usefulness of the possibility of locking to a point different from a resonance peak center, Fig. 9 shows an exceptionally flat MIR comb spectrum that was obtained by locking on the side of peak A using the SH signal at 1630 nm. The lock point is denoted by the green vertical line in Fig. 5.

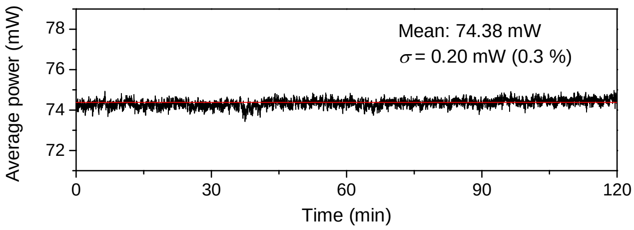

Fig. 8. Stability of the average output power of the SP-OPO mid-infrared frequency comb over 2 h. The sampling interval is 1 s.

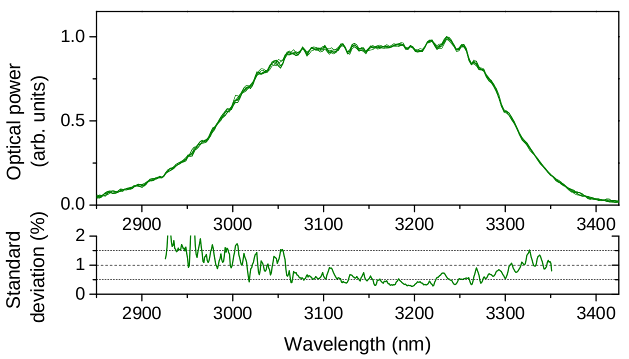

Fig. 9. Ten consecutive measurements of a flat MIR frequency comb envelope spectrum, which was obtained by locking on a side of the SP-OPO oscillation peak A using the modulation-free SH method. The lock point is indicated by a green vertical line in Fig. 5. Lower panel: the standard deviation of the ten spectra.

High spectral stability was obtained in the measurements reported here by stabilizing essentially a single point of the comb spectrum, using a single SH power detector. This was possible owing to the high power stability of the Er-fiber laser system that was used to pump the SP-OPO. The spectral stability would naturally be compromised in case of large average power fluctuations caused by instabilities of the pump laser or the SP-OPO cavity. In such cases a possible remedy is to measure the ratio of SH powers of two spectral points, albeit at the cost of increased experimental complexity. Stabilization of synchronously pumped lasers and OPOs by the measurement of relative powers of two different wavelengths within the emission spectrum has been reported before [12, 18-20]. Also the intra-cavity generated upconverted light, such as SH of the resonant beam, can be used to stabilize the SP-OPO cavity length, as well as the carrier-envelope offset of a singly-resonant SP-OPO [6, 21].

In conclusion, we have demonstrated a simple modulation-free method for robust locking of the oscillation of a degenerate femtosecond SP-OPO to the pump pulse train. The method provides a high spectral stability, which is crucial, e.g., for direct frequency comb spectroscopy. Additional benefits of the method include large locking bandwidth and the possibility of freely choosing the lock point so as to optimize the shape and width of the SP-OPO output spectrum. The method is generic, and can be applied to stabilization of singly-resonant SP-OPOs and SP-OPOs based on other crystal materials, such OP-GaAs crystals that are suitable for comb generation at longer infrared wavelengths [4].

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